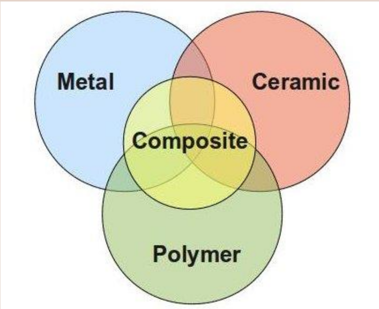
MEM30007A

Select common engineering materials



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Unit Resource Manual

Manufacturing Skills Australia Courses

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Aims of the Competency Unit:

This unit covers recognising common materials used in engineering, assisting in the selection of a material for a specific application, and using test results to evaluate the properties of materials.

Unit Hours:

36 Hours

Prerequisites:

Elements and Performance Criteria

1.	Identify common engineering materials by their principal properties	1.1	The principal properties of ferrous and non-ferrous metals are identified.
		1.2	The principal properties of thermosetting and thermoplastic polymers are identified
		1.3	The principal properties of ceramics and composite materials are identified.
		1.4	The effects of different types of bonding in materials are identified.
		1.5	The effects of mechanical and thermal processes on the principal properties of materials are identified.
2.	Select materials for specific applications	2.1	The engineering requirement for the specific application is determined in consultation with others.
		2.2	Material is selected based on the requirement and consideration of principal properties and further processing.
		2.3	Selection is confirmed according to standard operating procedures.
3.	Verify selected material as fit for purpose	3.1	Appropriate tests for the required properties are identified.
		3.2	Testing of materials is arranged with appropriate persons, if necessary.
		3.3	Test results are analysed and material choices are confirmed or modified as appropriate.

Required Skills and Knowledge

Required skills include:

- undertaking research
- selecting/carrying out tests appropriate to the material
- communicating
- documenting
- planning and sequencing operations
- reading, interpreting and following information on written job instructions, specifications, standard operating procedures, charts, lists, drawings and other applicable reference documents

Required knowledge includes:

- classification of materials:
    - metals and non-metals
    - ferrous and non-ferrous metals
    - polymers (thermoplastics, thermosetting and elastomers)
    - ceramics
    - composite materials
- structure of materials
- physical properties of materials:
    - electrical conductivity/resistivity
    - specific gravity/density
    - thermal conductivity/expansion
    - specific heat
    - melting/boiling points
- magnetic properties
- optical properties
- mechanical properties:
    - strength - yield, tensile, compressive
    - stress/strain data
    - hardness
    - toughness (impact and slow strain)
    - elasticity
    - plasticity
    - ductility
    - malleability
    - fatigue
    - creep
- chemical properties:
    - corrosion of metals, corrosion processes, mechanisms
    - degradation of polymers
- materials testing methods - destructive testing and applications:
    - tensile
    - compressive
    - shear
    - torsion
    - hardness
    - impact
    - fatigue

    - creep
    - visual
    - corrosion testing
- engineering materials
- engineering applications of ferrous metals:
    - cast irons
    - carbon and alloy steels
    - stainless steels
- engineering applications of non-ferrous metals:
    - aluminium and its alloys
    - copper, brass and bronze
    - nickel alloys, zinc, titanium
    - magnesium
    - refractory metals
- engineering applications of polymers:
    - thermosetting polymers
    - thermoplastic polymers
    - ceramics and glasses
- effects of mechanical and thermal processes on the properties of materials:
    - casting
    - forging, rolling and extrusion
    - cold forming
    - powder processes
    - heat treatment
    - joining - fasteners
    - soldering
    - brazing
    - welding
    - adhesives
    - finishing - coatings, metallic and non-metallic
- hazards and control measure associated with selecting common engineering materials, including housekeeping
- safe work practices and procedures

Lesson Program:

Unit hour unit and is divided into the following program.

Topic	Skill Practice Exercise
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Contents:

Topic 1 – Properties of Materials:

Required Skills:

On completion of the session, the participants will be able to:

- Recognise the link between the selection of materials for a product and the properties required of them by the product.
- Communicate in appropriate technical terms about the properties of materials.
- Recognise the properties characteristic of different groups of materials.

Required Knowledge:

- Processing formulae.
- Reading tables and charts.

Introduction to Selection of Materials:

The selection of a material for a component to be manufactured is as important as the design. The selection of a suitable material must be carefully thought out; information on the use of the component, working environment, wear, force and stress loading, aesthetics, compatibility of adjoining materials (galvanic corrosion) and financial constraints.

Material selection is a step in the process of designing any physical object. In the context of product design, the main goal of material selection is to minimize cost while meeting product performance goals. Systematic selection of the best material for a given application begins with properties and costs of candidate materials. For example, a thermal blanket must have poor thermal conductivity in order to minimize heat transfer for a given temperature difference.

Systematic selection for applications requiring multiple criteria is more complex. For example, a rod which should be stiff and light requires a material with high Young's modulus and low density. If the rod will be pulled in tension, the specific modulus, or modulus divided by density will determine the best material; because a plate's bending stiffness scales as its thickness cubed, the best material for a stiff and light plate is determined by the *cube root* of stiffness divided by density.

Question – What materials are used for a container of soft drink?
Answer – Soft drinks are manufactured in aluminium cans, glass or plastic bottles.

Question – What makes these materials suitable and others not?
Answer – In order to answer this question we need to investigate the properties of other materials.

Points to be considered in the selection of a material could be:

- Rigidity - the container does not stretch or become floppy under the content's weight.
- Strength – the container can stand the weight of the contents.
- Resistance to chemical attack from the contents.
- Retention of the gas component - prevent the gas from escaping through the container walls.
- Low density – so the container is not too heavy.

- Cost effectiveness – profit.
- Ease of manufacture – increases the profit.

The selection of a suitable material involves balancing a number of different specifications and making a choice of the material.

One of the best ways to collect research on materials is to carry out tests/experiments that will reflect their use in projects. For example, if the materials require for a project will need to be hardwearing, a test could be devised and tried out using several possible materials. The findings would be filed using a range of materials and mark/grade for each according to their resistance.

A range of tests could be devised to assess waterproof properties, impact resistance, flexibility rigidity, and many more.

The Rich Picture in **Error! Reference source not found.** shows the wide range of facts and issues relating to materials research that need to be considered when designing a product; this type of presentation could be the first page of materials research for a design project.

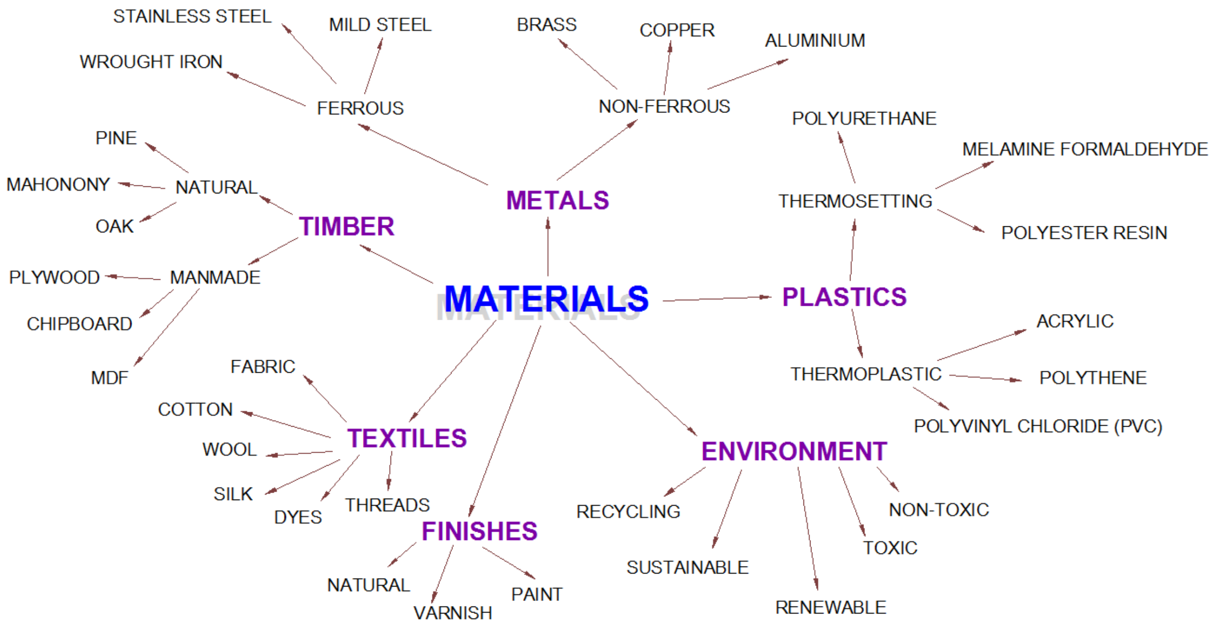

Figure 1.1

The selection of a material from which a product can be manufactured depends on a number of factors; these are often grouped under three main headings, namely:

1. The requirements imposed by the conditions under which the product is used, i.e. the service requirements; therefore, if a product is to be subject to forces then it might need strength, if subject to a corrosive environment then it might require corrosion resistance.
2. The requirements imposed by the methods proposed for the manufacture of the product. For example, if a material has to be bent as part of its processing, it must be ductile enough to be bent without breaking. A brittle material such as cast iron could not be used.
3. Cost.

Properties of materials

Materials selection for a product is based upon a consideration of the properties required including:

1. Mechanical properties –displayed when a force is applied to a material and include strength, stiffness, hardness, toughness and ductility.
2. Electrical properties –seen when the material is used in electrical circuits or components and include resistivity, conductivity and resistance to electrical breakdown.
3. Magnetic properties – relevant when the material is used as a magnet or part of an electrical component such as an inductor which relies on such properties.
4. Thermal properties – displayed when there is a heat input to a material and include expansivity and heat capacity.
5. Physical properties – the properties which are characteristic of a material and determined by its nature, including density, colour, surface texture.
6. Chemical properties - relevant in considerations of corrosion and solvent resistance.

The properties of materials are often changed markedly by the treatments they undergo; for example, steels can have their properties changed by heat treatment, such as annealing, which involves heating to some temperature and slowly cooling or quenching, i.e. heating and then immersing the material in cold water. Steel can also have its properties changed by working, for example, if a piece of carbon steel is permanently deform, it will have different mechanical properties from those existing before that deformation; refer to **Error! Reference source not found.** for more information.

Mechanical Properties:

The mechanical properties are about the behaviour of materials when subject to forces. When a material is subject to external forces, then internal forces are set up in the materials which oppose the external forces. The material can be considered to be similar to a spring. A spring, when stretched by external forces, sets up internal opposing forces which are readily apparent when the spring is released and they force it to contract. When a material is subject to external forces which stretch it then it is in ***tension*** (**Error! Reference source not found.**); when a material is subject to forces which squeeze it then it is in ***compression*** (**Error! Reference source not found.**). If a material is subject to forces which cause it to twist or one face to slide relative to an opposite face then it is said to be in ***shear*** (**Error! Reference source not found.**).

In discussing the application of forces to materials an important aspect is often not so much the size of the force as the force applied per unit area; thus, for example, if a strip of material is stretched by a force ***F*** applied over its cross-sectional area ***A,*** then the force applied per unit area is ***F/A.*** The term ***stress*** is used for the force per unit area.

Figure 1.2

Figure 1.3

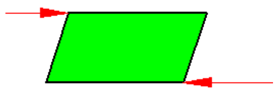

Figure 1.4

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

Stress has the units of pascal (Pa), with 1 Pa being a force of 1 newton per square metre, i.e. 1 Pa = 1 N/m^2. The stress is said to be ***direct stress*** when the area being stressed is at right angles to the line of action of the external forces, as when the material is in tension or compression. Shear stresses are not direct stresses since the forces being applied are in the same plane as the area being stressed. The area used in calculations of the stress is generally the original area that existed before the application of the forces. The stress is thus sometimes referred to as the ***engineering stress,*** the term ***true stress*** being used for the force divided by the actual area existing in the stressed state.

When a material is subject to tensile or compressive forces it changes in length. The formula to determine ***strain*** is:

$$\text{Strain} = \frac{\text{Change in Length}}{\text{Original Length}}$$

Since strain is a ratio of two lengths it has no units. Thus we might, for example, have a strain of 0.01. This would indicate that the change in length is 0.01 x the original length. However, strain is frequently expressed as a percentage.

$$\text{Strain as a \%} = \frac{\text{Change in Length}}{\text{Original Length}} \times 100$$

Therefore, the strain of 0.01 as a percentage is 1%, i.e. this is when the change in length is 1% of the original length.

Example:
A strip of material has a length of 50 mm. When it is subject to tensile forces it increases in length by 0.020 mm. What is the strain? The strain is the change in length divided by the original length:

$$\text{Strain} = \frac{0.020}{50} = 0.0004$$

Expressed as a percentage, the strain is:

$$\textit{Strain} = \frac{0.020}{50} \times 100 = 0.04\%$$

Strength:

In materials science, the strength of a material is its ability to withstand an applied stress without failure. The field of strength of materials deals with loads, deformations and the forces acting on a material. A load applied to a mechanical member will induce internal forces within the member called stresses. The stresses acting on the material cause deformation of the material. Deformation of the material is called strain, while the intensity of the internal forces is called stress. The applied stress may be tensile, compressive, or shear. The strength of any material relies on three different types of analytical method: strength, stiffness and stability, where strength refers to the load carrying capacity, stiffness refers to the deformation or elongation, and stability refers to the ability to maintain its initial configuration. Material yield strength refers to the point on the engineering stress-strain curve (as opposed to true stress-strain curve) beyond which the material experiences deformations that will not be completely reversed upon removal of the loading. The ultimate strength refers to the point on the engineering stress-strain curve corresponding to the stress that produces fracture.

$$\text{Tensile Strength} = \frac{\text{Maximum Tensile Force}}{\text{Original Cross-Sectional Area}}$$

The compressive strength and shear strength are defined in a similar way. The unit of strength is the pascal (Pa), with 1 Pa being 1 N/m^2. Strengths are often millions of pascals and so the MPa is often used, 1 MPa being 106 Pa or 1 million Pa.

Often it is not the strength of a material that is important in determining the situations in which a material can be used but the value of the stress at which the material begins to yield. If gradually increasing tensile forces are applied to, say, a strip of mild steel then initially when the forces are released the material springs back to its original shape. The material is said to be ***elastic.*** If measurements are made of the extension at different forces and a graph plotted, then the extension is found to be proportional to the force and the material is said to obey ***Hooke's law.*** However, when a particular level of force is reached the material stops springing back completely to its original shape and is then said to show some ***plastic*** behaviour. This point coincides with the point on a force-extension graph at which the graph stops being a straight line graph, the so-called ***limit of proportionality.***

Error! Reference source not found. shows the type of force-extension graph which would be given by a sample of mild steel. The limit of proportionality is point A. Up to this point Hooke's law is obeyed and the material shows elastic behaviour, beyond it shows a mixture of elastic and plastic behaviour. Dividing the forces by the initial cross-sectional area of the sample and the extensions by the original length converts the force-extension data into a stress-strain graph, as in **Error! Reference source not found.**. The stress at which the material starts to behave in a non-elastic manner is called the ***elastic limit.*** Generally at almost the same stress the material begins to stretch without any further increase in force and is said to have yielded. The term ***yield stress*** is used for the stress at which this occurs; for some materials, such as mild steel, there are two yield points, termed the upper and the lower yield points. A carbon steel typically might have a tensile strength of 600 MPa and a yield stress of 300 MPa.

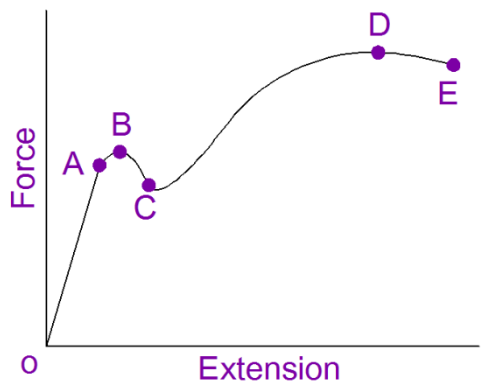

Figure 1.5 – Force Extension Graph

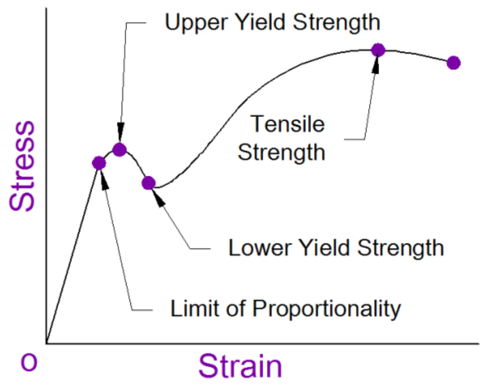

Figure 1.6 – Stress Strain Graph

Where:

A = Limit of Proportionality
B = Upper Yield Point
C = Lower Yield Point
D = Maximum Force
E = Breaking Point

In some materials, such as aluminium alloys, the yield stress is not so easily identified as with mild steel and the term ***proof stress*** is used as a measure of when yielding begins; this is the stress at which the material has departed from the straight-line force-extension relationship by some specified amount. The 0.1% proof stress is defined as that stress which results in a 0.1% offset, i.e. the stress given by a line drawn on the stress-strain graph parallel to the linear part of the graph and passing through the 0.1% strain value, as in **Error! Reference source not found.**. A 0.2% proof stress is likewise defined as that stress which results in a 0.2% offset.

Since Stress is Force/Area then:

Figure 1.7 – Determination of Proof Stress

Yield Force = Yield Stress x Area

$= 200 \times 10^{6} \times 100 \times 10^{-6}$

$= 20000N$

or 20kN

Example:
Samples are taken of cast aluminium alloys and give the following data. Which is the strongest in tension?

LM4 tensile strength 140 MPa
LM6 tensile strength 160 MPa
LM9 tensile strength 170 MPa

The strongest in tension is the one with the highest tensile strength and is LM9.

Stiffness:

The ***stiffness*** of a material is the ability of a material to resist bending; when a strip of material is bent, one surface is stretched and the opposite face is compressed, as illustrated in **Error! Reference source not found.**.

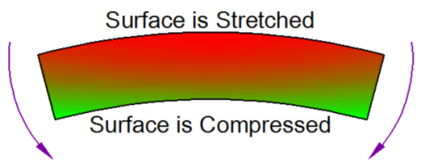

Figure 1.8 - Bending

The more a material bends, the greater is the amount by which the stretched surface extends and the compressed surface contracts. Therefore, a stiff material would be one that undergoes a small change in length when subject to such forces; this means a small strain when subject to such stress and so a small value of strain/stress, or conversely a large value of stress/strain. For most materials a graph of stress against strain gives initially a straight-line relationship, as illustrated in **Error! Reference source not found.**. Thus a large value of stress/strain means a steep slope of the stress-strain graph. The quantity stress/strain when we are concerned with the straight-line part of the stress-strain graph is called the ***modulus of elasticity*** (or sometimes ***Young's modulus)***.

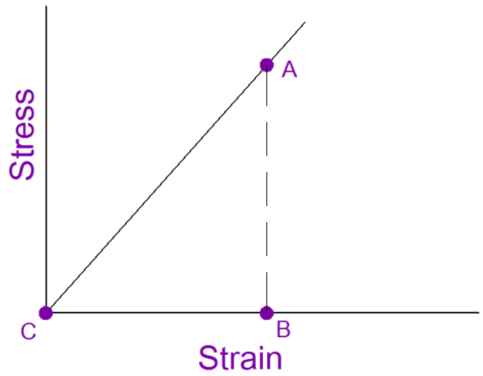

Figure 1.9 – Modulus of Elasticity = AB/BC

$$\text{Modulus of Elasticity} = \frac{\text{Stress}}{\text{Strain}}$$

The units of the modulus are the same as those of stress, since strain has no units. Engineering materials frequently have a modulus of the order of 1000 million Pa, i.e. 10^{9} Pa; this is generally expressed as GPa, with 1 GPa = 10^{9} Pa. Typical values are about 200 GPa for steels and about 70 GPa for aluminium alloys. A stiff material therefore has a high modulus of elasticity. Consequently steels are stiffer than aluminium alloys; for most engineering materials the modulus of elasticity is the same in tension as in compression.

Example:
If a material of a component has a tensile modulus of elasticity of 200 GPa, what strain will be produced by a stress of 4 MPa?

Since the modulus of elasticity is stress/strain then:

$$\text{Strain} = \frac{\text{Stress}}{\text{Modulus}} = \frac{4 \times 10^6}{200 \times 10^9} = 0.00002$$

Example:
Which of the following plastics is the stiffest?

ABS	Tensile Modulus 2.5 GPa
Polycarbonate	Tensile Modulus 2.8 GPa
Polypropylene	Tensile Modulus 1.3 GPa
PVC	Tensile Modulus 3.1 GPa

The stiffest plastic is the one with the highest tensile modulus and therefore is the PVC.

Ductility or Brittleness:

When a glass is dropped and breaks then it is possible (but not probable) to stick all the pieces together again and restore the glass to its original shape. The glass is said to be a ***brittle*** material.

Using the previous example of a soft drink container, if a steel or aluminium can is dropped, the can is less likely to shatter like a glass bottle but more likely to show permanent deformation in the form of dents. The material has shown plastic deformation which the term ***permanent deformation*** is used to changes in dimensions which are not removed when the forces applied to the material are taken away. Materials which develop significant permanent deformation before they break are called ***ductile.*** **Error! Reference source not found.** and **Error! Reference source not found.** show the types of stress-strain graphs given by brittle and ductile materials, the ductile one indicating a considerable extent of plastic behaviour.

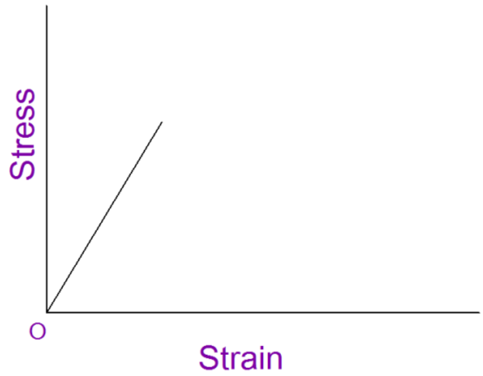

Figure 1.10 – Brittle Materials

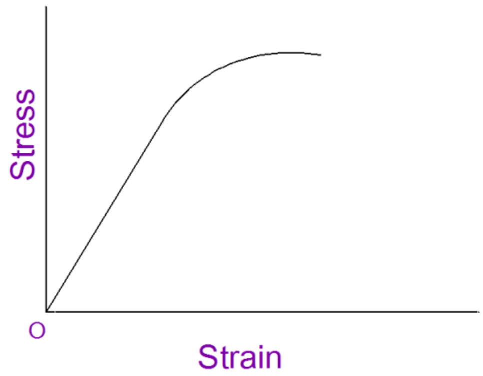

Figure 1.11 – Ductile Materials

A measure of the ductility of a material is obtained by determining the length of a test piece of the material, then stretching it until it breaks and then, by putting the pieces together, measuring the final length of the test piece, as illustrated in Figure 1.8. A brittle material will show little change in length from that of the original test piece, but a ductile material will indicate a significant increase in length. The measure of the ductility is then the ***percentage elongation***.

$$\% \text{ elongation} = \frac{\text{Final} - \text{Initial Lengths}}{\text{Initial Length}} \times 100$$

A reasonably ductile material, such as mild steel, will have an elongation of about 20%, or more. A brittle material, such as a cast iron, will have an elongation of less than 1%

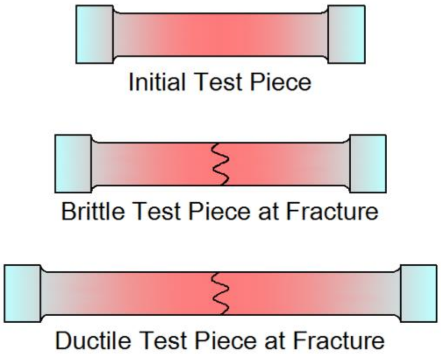

Figure 1.12 – Test Pieces after Fracture

Example
A material has an elongation of 10%. By how much longer will be a strip of the material of initial length 200 mm when it breaks? The percentage elongation can be expressed as

$$\% \text{ elongation} = \frac{\text{Change in Length}}{\text{Original Length}} \times 100$$

Therfore

$$\text{Changes in Length} = \frac{10 \times 200}{100} = 20 \text{ mm}$$

Example
Which of the following materials is the most ductile?

80-20 brass % elongation 50%
70-30 brass % elongation 70%
60-40 brass % elongation 40%

The most ductile material is the one with the largest percentage elongation, therefore the 70-30 brass.

Toughness:

A tough material can be considered to be one that resists breaking meaning that a tough material requires more energy to break it than a less tough one. There are, however, a number of measures that are used for toughness. Consider a length of material being stretched by tensile forces; when it is stretched by an amount as a result of a constant force F_1 then the work done is:

Work = Force (F) x extension (y)

Work = $F_1 y_1$

Therefore, if a force-extension graph is considered as shown in **Error! Reference source not found.**, the work done when a very small extension is considered, is the area of that strip under the graph. The total work done in stretching a material to an extension y_1, i.e. through an extension which we can consider to be made up of a number of small extensions, is thus:

$$Work = F_1\, y_1 + F_2\, y_2 + F_3\, y_3 + ...$$

and so is the area under the graph up to ***x***.

Since stress = force/area and strain - extension/length then:

Work = (stress X area) X (strain X length)

Since the product of the area and length is the volume of the material, then:

Work/volume = stress X strain

Thus the work done in stretching a material unit volume to a particular strain is the sum of the work involved in stretching the material to each of the strains up to this strain.

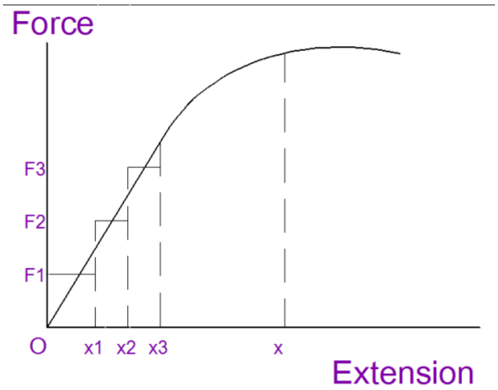

Figure 1.13

The area under a force-extension graph up to the breaking point is thus a measure of the energy required to break the material. The area under the stress-strain graph up to the breaking point is a measure of the energy required to break a unit volume of the material. A large area is given by a material with a large yield stress and high ductility (see **Error! Reference source not found.** and **Error! Reference source not found.**). Such materials can thus be considered to be tough.

An alternative way of considering toughness is the ability of a material to withstand shock loads. A measure of this ability to withstand suddenly applied forces is obtained by ***impact tests,*** such as the Charpy and Izod tests (refer to **Error! Reference source not found.**). In these tests, a test piece is struck a sudden blow and the energy needed to break it is measured. The results are thus expressed in units of energy, i.e. joules (J). A brittle material will require less energy to break it than a ductile one. The results of such tests are often used as a measure of the brittleness of materials.

Another measure of toughness that can be used is fracture toughness. ***Fracture toughness*** can be defined as a measure of the ability of a material to resist the propagation of a crack. The toughness is determined by loading a sample of the material which contains a deliberately introduced crack of length ***2c*** and recording the tensile stress a at which the crack propagates. The fracture toughness, symbol K_c and usual units MPa $m^{1/2}$, is given by:

$$K_c = \sigma \sqrt{\pi c}$$

The smaller the value of the toughness, the more readily a crack propagates. The value of the toughness depends on the thickness of the material, high values occurring for thin sheets and decreasing with increasing thickness to become almost constant in thick sheets. For this reason, a value called the ***plane strain fracture toughness*** K_{Ic} is often quoted; this is the value of the toughness that would be obtained with thick sheets. Typical values are of the order of 1 MPa $m^{1/2}$ for glass, which readily fractures when there is a crack present, to values of the order of 50 to 150 MPa $m^{1/2}$ for some steels and copper alloys. In such materials cracks do not readily propagate.

Hardness:

The ***hardness of a material*** is a measure of its resistance to abrasion or indentation. A number of scales are used for hardness, depending on the method that has been used for measuring. **The *hardness of a material*** is a measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied. Macroscopic hardness is generally characterized by strong intermolecular bonds, but the behavior of solid materials under force is complex; therefore, there are different measurements of hardness: *scratch hardness*, *indentation hardness*, and *rebound hardness*.

The hardness is roughly related to the tensile strength of a material, the tensile strength being roughly proportional to the hardness (refer to **Error! Reference source not found.**); therefore, the higher the hardness of a material, the higher is likely to be the tensile strength.

Hardness is dependent on ductility, elastic stiffness, plasticity, strain, strength, toughness, viscoelasticity, and viscosity.

Common examples of **hard matter** are ceramics, concrete, certain metals, and superhard materials, which can be contrasted with soft matter.

Electrical Properties:

The electrical ***resistivity*** (p) is a measure of the electrical resistance of a material, being defined by the equation:

$$P = \frac{RA}{L}$$

where ***R*** is the resistance of a length ***L*** of the material of cross-sectional area ***A.*** The unit of resistivity is the ohm metre. An electrical insulator such as a ceramic will have a very high resistivity, typically of the order of 10^{10} Ω m or higher. An electrical conductor such as copper will have a very low resistivity, typically of the order of 10^{10} Ω m.

The electrical ***conductance*** of a length of material is the reciprocal of its resistance and has the unit of $\boldsymbol{Q^{-1}}$; this unit is given a special name of siemens (S). The electrical ***conductivity*** (a) is the reciprocal of the resistivity:

$$\Omega = \frac{1}{\Omega} = \frac{L}{RA}$$

The unit of conductivity is thus Ω^{-1} m or S m^{-1}. Since conductivity is the reciprocal of the resistivity, an electrical insulator will have a very low conductivity, of the order of 10^{-10} S/m, while an electrical conductor will have a very high one, of the order of 10^{8} S/m.

The ***dielectric strength*** is a measure of the highest voltage that an insulating material can withstand without electrical breakdown. It is defined as:

$$\text{Dielectric Strength} \; \frac{\text{Breakdown Voltage}}{\text{Insulator Thickness}}$$

The units of dielectric strength are volts per metre. Polythene has a dielectric strength of about 4 x 10^{7} V/m; this means that a 1 mm thickness of polythene will require a voltage of about 40 000 V across it before it will break down.

Example

An electrical capacitor is to be made with a sheet of polythene of thickness 0.1 mm between the capacitor plates. Determine the greatest voltage that can be connected between the capacitor plates if there is not to be electrical breakdown? Take the dielectric strength to be 4×10^7 V/m. The dielectric strength is defined as the breakdown voltage divided by the insulator thickness, hence:

$$\text{Breakdown Voltage} = \text{Dielectric Strength} \times \text{Thickness}$$
$$= 4 \times 10^7 \times 0.1 \times 10^{-3}$$
$$= 4000 \text{ V}$$

Thermal Properties:

The SI unit of temperature is the kelvin with a temperature change of 1 K being the same as a change of 1°C. The **kelvin** is a unit of measurement for temperature. It is one of the seven base units in the International System of Units (SI) and is assigned the unit symbol **K**. The Kelvin scale is an absolute, thermodynamic temperature scale using as its null point absolute zero, the temperature at which all thermal motion ceases in the classical description of thermodynamics. The kelvin is defined as the fraction $^1/_{273.16}$ of the thermodynamic temperature of the triple point of water (exactly 0.01 °C or 32.018 °F).

The ***linear expansivity*** (a) or ***coefficient of linear expansion*** is a measure of the amount by which a length of material will expand when the temperature increases and is defined as:

$$\alpha = \frac{\text{Change in Length}}{\text{Original Length x Change in Temperature}}$$

It has the unit of K^{-1}.

The ***specific heat capacity*** (c) is a measure of the amount of heat needed to raise the temperature of the material. It is defined as:

$$c = \frac{\text{Amount of Heat}}{\text{Mass x Change in Temperature}}$$

c has the unit of J kg^{-1} K^{-1}. Weight-for-weight metals require less heat to reach a particular temperature than plastics. This is because metals have smaller specific heat capacities. For example, copper has a specific heat capacity of about 340 J kg^{-1} K^{-1} while polythene is about 1800 J kg^{-1} K^{-1}.

The ***thermal conductivity*** \f a material is a measure of its ability to conduct heat. There will only be a net flow of heat energy through a length of material when there is a difference in temperature between the ends of the material. Thus the thermal conductivity is defined in terms of the quantity of heat that will flow per second through a temperature gradient.

$$\lambda = \frac{\text{Quantity of Heat/Second}}{\text{Temperature Gradient}}$$

λ has the unit of W m^{-1} K^{-1}. A high thermal conductivity means a good conductor of heat. Metals tend to be good conductors. For example, copper has a thermal conductivity of about 400 W m^{-1} K^{-1}. Materials which are poor conductors of heat have low thermal conductivities. For example, plastics have thermal conductivities of the order of 0.03 W m^{-1} K^{-1}.

Example

A designer of domestic pans requires a material for a handle which would enable a hot pan to be picked up with comfort, the handle not getting hot. What quantity should he or she look for in tables in order to find a suitable material?

What is required is a material with a low thermal conductivity, probably a small fraction of a W m^{-1} K^{-1}.

Physical Properties:

Physical properties are those that can be observed without changing the identity of the substance. The general properties of matter such as colour, density, hardness, are examples of physical properties. Properties that describe how a substance changes into a completely different substance are called chemical properties. Flammability and corrosion/oxidation resistance are examples of chemical properties.

The ***density*** *(*p) of a material is the mass per unit volume.

$$p = \frac{\text{Mass}}{\text{Volume}}$$

It has the unit of kg/m^3. It is often an important property that is required in addition to a mechanical property; thus, for example, an aircraft undercarriage is required to be not only strong but also of low mass. Therefore, what is required is as high a strength as possible with as low a density as possible, i.e. a high value of strength/density; this quantity is often referred to as the ***specific strength.*** Steels tend to have specific strengths of the order of 50 to 100 MPa/Mg m^{-3} (note: 1 Mg is 10^6 g or 1000 kg), magnesium alloys about 140 MPa/Mkg m^{-3} and titanium alloys about 250 MPa/Mkg m^{-3}. **F**or example, a lower-strength magnesium alloy would be preferred to a higher-strength, but higher-density, steel.

Chemical Properties:

Chemical and physical properties may often be tabulated together in most handbooks. In general, the data associated with a compound contain name, empirical and structural formula, molecular weight, Chemical Abstract (CA) registry number, melting point, boiling point, density, color, solubility, oxidation or reduction potential, and various spectroscopic peaks. However, other literature must be consulted on chemical reactivity.

Chemical reactions usually involve the breakage and formation of some chemical bonds. All chemical reactions involve the redistribution of electrons among species involved. Chemical properties show the nature of its reactivity, the type of compounds and the category of reactions. Think of a compound, and classify it according to the following criteria.

Attack on materials by the environment in which they are situated is a major problem. The rusting of iron is an obvious example. Tables are often used giving the comparative resistance to attack of materials in various environments, e.g. in aerated water, in salt water, to strong acids, to strong alkalis, to organic solvents, to ultraviolet radiation. Thus, for example, in a salt water environment carbon steels are rated at having very poor resistance to attack, aluminium alloys good resistance and stainless steels excellent resistance.

The Range of Materials:

Materials are usually classified into four main groups, these being metals, polymers and elastomers, ceramics and glasses, and composites. The following is a brief comparison, in general, of the properties of these main groups. Differences in the internal structure of the groups are discussed in **Error! Reference source not found.**

Property	Metals	Polymers	Ceramics
Density (Mg m^{-3})	2 – 16	1 – 2	2 – 17
Melting Point (°C)	200 – 3500	70 – 200	2000 - 4000
Thermal Conductivity	High	Low	Medium
Thermal Expansion	Medium	High	Low
Specific Heat Capacity	Low	Medium	High
Electrical Conductivity	High	Very Low	Very Low
Tensile Strength (MPa)	100 – 2500	30 – 300	40 – 400
Tensile Modulus (GPa)	40 – 400	0.7 – 3.5	150 – 450
Hardness	Medium	Low	High
Resistance to Corrosion	Medium – Poor	Good – Medium	Good

Note: 1 Mg m^{-1} = 1000kg m^{-3}

Figure 2. 1.1 – Range of Properties

Metals:

Engineering metals are generally alloys. The term alloy is used for metallic materials formed by mixing two or more elements. For example, mild steel is an alloy of iron and carbon, stainless steel is an alloy of iron for adding elements to the iron is to improve the iron's properties. Pure metals are very weak materials. The carbon improves the strength of the iron. The presence of the chromium in the stainless steel improves the corrosion resistance.

The properties of any metal are affected by the treatment it has received and the temperature at which it is being used. Thus heat treatment, working and interaction with the environment can all change the properties. In general, metals have high electrical and thermal conductivities, can be ductile and thus permit products to be made by being bent into shape, and have a relatively high modulus of elasticity and tensile strength.

Polymers and Elastomers:

Thermoplastics soften when heated and become hard again when the heat is removed. The term implies that the material becomes plastic when heat is applied. Thermosets do not soften when heated, but char and decompose; therefore thermoplastic materials can be heated and bent to form required shapes, while thermosets cannot. Thermoplastic materials are generally flexible and relatively soft. Polythene is an example of a thermoplastic, being widely used in the forms of films or sheet for such items as bags, squeeze bottles, and wire and cable insulation. Thermosets are rigid and hard. The popular phenol formaldehyde used in the past was known as Bakelite but has largely been replaced by PP (polypropylene) and PE (polythene) in the modern industry; Bakelite is a thermoset and was widely used for electrical plug casings, door knobs and handles.

The term elastomers is used for polymers which by their structure allow considerable extensions that are reversible. The material used to make rubber bands is an obvious example of such a material.

All thermoplastics, thermosets and elastomers have low electrical conductivity and low thermal conductivity, hence their use for electrical and thermal insulation. Compared with metals, they have lower densities and higher coefficients of expansion, are generally more corrosion resistant, have a lower modulus of elasticity, tensile strengths which are nearly as high as metals, are not as hard, and give larger elastic deflections. When loaded they tend to creep, i.e. the extension gradually changes with time; their properties depend very much on the temperature so that a polymer which may be tough and flexible at room temperature may be brittle at 0°C and creep at a very high rate at 100°C.

Ceramics and Glasses:

Ceramics and glasses tend to be brittle, have a relatively high modulus of elasticity, are stronger in compression than in tension, are hard, chemically inert, and have low electrical conductivity. Glass is just a particular form of ceramic, with ceramics being crystalline and glasses non-crystalline. Examples of ceramics and glasses abound in the home in the form of cups, plates and glasses. Alumina, silicon carbide, cement and concrete are examples of ceramics; because of their hardness and abrasion resistance, ceramics are widely used for the cutting edges of tools.

Composites:

Composites are materials composed of two different materials bonded together in such a way that one serves as the matrix and surrounds the fibres or particles of the other. There are composites involving glass fibres or particles in polymers, ceramic particles in metals (referred to as cermets) and steel rods in concrete (referred to as reinforced concrete). Timber is a natural composite consisting of tubes of cellulose in a natural polymer called lignin.

Composites are able to combine the good properties of other types of materials while avoiding some of their drawbacks. Composites can be made low density, with strength and a high modulus of elasticity; however, they generally tend to be more expensive to produce.

Costs:

These can be considered in relation to the basic costs of the raw materials, the costs of manufacturing and the life and maintenance costs of the finished product.

Comparison of the basic costs of materials is often on the basis of the cost per unit weight or cost per unit volume; for example, if the cost of 10 kg of a metal is, say, $15 then the cost per kg is $1.50. f the metal has a density of 8000 kg/m^3 then 10 kg will have a volume of 10/8000 = 0.00125 m^3 and so the cost per cubic metre is 1.5/0.00125 = $1200. The formulae to determine the cost per m^3 can be written as:

$$\text{Cost per m}^3 = (\text{Cost per Kilogram}) \times \text{Density}$$

However, often a more important comparison is on the basis of per unit strength or cost per unit stiffness for the same volume of material; this enables the cost of, say, a beam to be considered in terms of what it will cost to have a beam of a certain strength or stiffness. Hence if, for comparison purposes, a beam of volume 1 m^3 is considered then if the tensile strength of the above material is 500 MPa, the cost per MPa of strength will be 1200/500 = $2.40. The formulae to determine the same volume is:

$$\text{Cost per unit strength} = \frac{(\text{Cost/m}^3)}{\text{Strength}}$$

and similarly

$$\text{Cost per unit strength} = \frac{(\text{Cost/m}^3)}{\text{Stiffness}}$$

The costs of manufacturing will depend on the processes used. Some processes require a large capital outlay and then can be employed to produce large numbers of the product at a relatively low cost per item. Others may have little in the way of setting-up costs but a large cost per unit product. The cost of maintaining a material during its life can often be a significant factor in the selection of materials. A feature common to many metals is the need for a surface coating to protect them from corrosion by the atmosphere. The rusting of steels is an obvious example of this and dictates the need for such activities as the continuous repainting of the Sydney Harbour Bridge.

Figure 1.14

In **Error! Reference source not found.** above, the main supporting arch is showing clear signs of rust and needs immediate descaling and repainting.

Example

On the basis of the following data, compare the costs per unit strength of the two materials for the same volume of material.

Low-carbon Steel: Cost per kg $1.00, density 7800 kg/$m^3$, strength 1000 MPa

Aluminium Alloy (Mn): Cost per kg $2.20, density 2700 kg/$m^3$, strength 200MPa

For the steel, the volume of 1 kg is 1/7800 = 0.00013 m^3 and so the cost per m^3 is 1/0.00013 = $7692. The cost per MPa of strength is thus 7692/1000 = $7.69. For the aluminium alloy, the volume of 1 kg is 1/2700 = 0.00037 m^3 and so the cost per m^3 is 02.2/0.00037 = $5946; therefore, although the cost per kg is greater than that of the steel, because of the lower density the cost per cubic metre is less. The cost per MPa of strength is 5946/200 = $29.73. On a comparison on the strengths of equal volumes, it is cheaper to use the steel where $7.69 < $29.73.

Review Problems:

MEM30007-RQ-01

1. What types of properties would be required for the following products?
   (a) A domestic kitchen sink.
   (b) A shelf on a bookcase.
   (c) A cup.
   (d) An electrical cable.
   (e) A coin.
   (f) A car axle.
   (g) The casing of a telephone.

2. For each of the products listed in problem 1, identify a material that is commonly used and explain why its properties justify its choice for that purpose.

3. Which properties of a material would you need to consider if you required materials which were:
   (a) Stiff,
   (b) Capable of being bent into a fixed shape.
   (c) Capable of not fracturing when small cracks are present.
   (d) Not easily broken.
   (e) Acting as an electrical insulator.
   (f) A good conductor of heat.
   (g) Capable of being used as the lining for a tank storing acid.

4. A colleague informs you that a material has a high tensile strength with a low percentage elongation. Explain how you would expect the material to behave.

5. A colleague informs you that a material has a high tensile modulus of elasticity and good fracture toughness. Explain how you would expect the material to behave.

6. What is the tensile stress acting on a strip of material of cross-sectional area 50 mm^2 when subject to tensile forces of 1000 N?

7. Tensile forces act on a rod of length 300 mm and cause it to extend by 2 mm. What is the strain?

8. An aluminium alloy has a tensile strength of 200 MPa. What force is needed to break a bar of this material with a cross-sectional area of 250mm^2?

9. A test piece of a material is measured as having a length of 100 mm before any forces are applied to it. After being subject to tensile forces it breaks and the broken pieces are found to have a combined length of 112 mm. What is the percentage elongation?

10. A material has a yield stress of 250 MPa. What tensile forces will be needed to cause yielding i f the material has a cross-sectional area of 200 mm^2?

11. A sample of high tensile brass is quoted as having a tensile strength of 480 MPa and an elongation of 20%. An aluminium-bronze is quoted as having a tensile strength of 600 MPa and an elongation of 25%. Explain the significance of these data in relation to the mechanical behaviour of the materials.

12. A grey cast iron is quoted as having a tensile strength of 150 MPa, a compressive strength of 600 MPa and an elongation of 0.6%. Explain the significance of the data in relation to the mechanical behaviour of the material.

13. A sample of carbon steel is found to have an impact energy of 120 J at temperatures above 0°C and 5 J below it. What is the significance of these data?

14. Mild steel is quoted as having an electrical resistivity of 1.6×10^{-7}. Is it a good conductor of electricity?
15. A colleague states that he needs a material with a high electrical conductivity. Electrical resistivity tables for materials are available. What types of resistivity values would you suggest he looks for?
16. Aluminium has a resistivity of 2.5 x 10-8Ω m. What will be the resistance of an aluminium wire with a length of 1 m and a cross-sectional area of 2 mm^2?
17. How do the properties of thermoplastics differ from those of thermosets?
18. You read in a textbook that "Designing with ceramics presents problems that do not occur with metals because of the almost complete absence of ductility with ceramics". Explain the significance of the comment in relation to the exposure of ceramics to forces.
19. Compare the specific strengths, and costs per unit strength for equal volumes, for the materials giving the following data:
    Low-carbon steel: Cost per kg $0.10, density 7800 kg/m^3, strength 1000 MPa
    Polypropylene: Cost per kg $0.20, density 900 kg/m^3, strength 30 MPa.